

STUDY ON A THERMOACOUSTIC-STIRLING ELECTRICAL GENERATOR

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ABSTRACT

In this work, a thermoacoustic-Stirling electrical generator (TASEG) was designed, analyzed and tested. First, the TASEG experimental setup was constructed. Then, a numerical analysis on the linear alternator was made. From the numerical simulation, it was found that the working frequency and electrical load, which are two factors to determine mechanical and electrical resonant state of the LA, significantly affect the LA to achieve maximum efficiency and output electrical power. Moreover, the whole experimental system was modeled and analyzed based on thermoacoustic theory. In the preliminary experiments, different operating parameters including heating power, heat temperature, and electrical load on the global performance were tested. At the most powerful point, the prototype TASEG can deliver more than 100W of electrical power under the operating condition of 2.5MPa mean pressure and 64Hz resonant frequency.

1. INTRODUCTION

In recent decades, thermoacoustic heat engines have been widely investigated to meet both energy saving and environment protection requirements. They have been developed as new devices capable of converting heat to acoustic power (i.e. mechanical work) without any moving parts, which potentially give high reliability, environmental friendliness and extensive energy source adaptability including solar energy and industrial waste heat. Moreover,

the thermoacoustic-Stirling heat engine (TASHE) promises high heat-to-acoustic conversion efficiency because of reversible thermodynamic process between the working gas and the regenerator. Using the acoustic power generated by the TASHE, we can realize the heat-to-electric power converting by coupling with a linear alternator (LA), which will be the focus of this paper. In the past years, great progresses have been made on the research of the TASHE. In 1999, Backhaus and Swift developed a TASHE which could achieve 30% heat-to-acoustic conversion efficiency (comparable to 25%-40% efficiency of the conventional internal combustion engine) and a maximum acoustic power of about 710W [1]. In 2004, Luo et al reported an energy-focused TASHE with a tapered resonance tube which could achieve a high pressure ratio above 1.3 with helium gas [2] and a net acoustical power output of more than 450W [3].

Furthermore, using the unwearing clearance sealing technology supported by flexure bearings, electro-dynamic LA can transform the acoustic power to electric power by oscillating motion with high efficiency and reliability. It was firstly proved in 2004 by Backhaus that the thermoacoustic-Stirling electric generator (TASEG) could be developed by coupling a TASHE with a LA [4]. Their experimental results gave a 58W electrical power with 0.15 heat-to-electric conversion efficiency. This paper will report our effort in developing a 100W-class TASEG.

2. EXPERIMENTAL SETUP

The thermoacoustic-Stirling electric generator in our experiments consists of a complete TASHE and a LA, which is shown in Fig.1. The TASHE typically has a loop and a resonance tube. Unlike the system configuration of [4] which directly couples a TASHE loop with a LA, the resonance tube is necessary in our system because the LA is not designed for the TASHE loop and the system can not work without the resonance tube.

The TASHE loop is about 2m long with 80mm inner diameter (i.d.), which successively consists of a 1555mm long feedback tube, a 45mm long main ambient heat exchanger (HX), a 80mm long regenerator filled with 120 mesh stainless steel screens, a 58mm long heater block, a 240mm long thermal buffer tube and a 22mm long secondary ambient HX. All ambient HXs are cooled by 15 °C circulating water. And the resonance tube is made up of a 0.5m long 80mm i.d. straight tube, a 5m long tapered tube with i.d. changing gradually from 80 to 300 mm and a 1m long 300mm i.d. straight tube with a capped end. More details of the TASHE can be found in [2] and [3]. The P and T in Fig.1 show the monitoring locations of heating temperature and pressure amplitude at the inlet of the LA. The LA manufactured is a dual-opposed configuration, which has pistons of 29.2mm (1.15in) diameter. Additionally, a maximum stroke of the pistons is limited to 10mm, and the maximum winding current should not beyond 1A. More structure details including mechanical-electrical transduction coefficient τ , mechanical spring stiffness K, moving mass M, mechanical damp R_m , winding inductance coefficient L_s and resistance r are given in TABLE 1. The windings of the LA are serially connected to an electric resistance R which can be varied from 0 to 170 Ω . The connecting pipe of the LA is 0.2m long with 50mm i.d. and branches out at the right end of the iso-diameter part of the resonance tube. The current and voltage signals of the load resistance are measured to calculate the electric power.

TABLE 1. SOME PARAMETERS OF EACH LA

	τ N/A	K N/mm	M kg	R_{mech} N·s/m	L_s mH	r Ω
LA	52.0	35.14	0.45	3.14	83.2	6.97

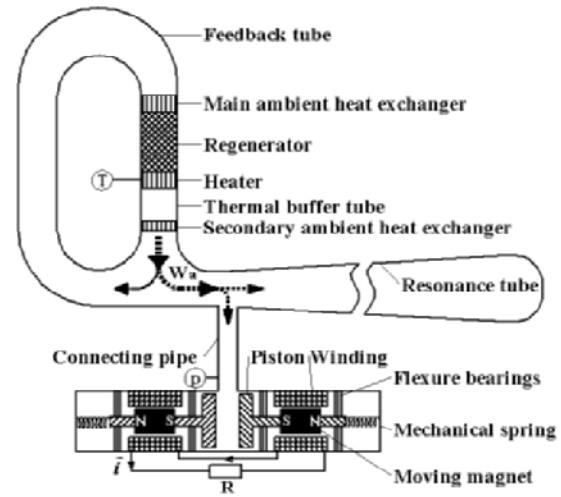


Fig. 1: Schematic diagram of the TASEG.

3. NUMERICAL SIMULATION OF THE TASEG

For a better understanding the performance of the TASEG, numerical simulations are performed at first. The computational model of the TASHE is based on the linear thermoacoustic theory with the following thermoacoustic equations[5]:

$$\frac{d\hat{U}}{dx} + \frac{i\omega A}{\gamma P_0} [1 + (\gamma - 1)f_k] \hat{P} - \frac{f_k - f_\mu}{(1 - f_\mu)(1 - \sigma) T_m} \hat{U} \frac{dT_m}{dx} = 0 \quad (1)$$

$$\frac{d\hat{P}}{dx} + \frac{i\omega \rho_m}{A(1 - f_\mu)} \hat{U} = 0 \quad (2)$$

$$\frac{dH}{dx} = Q \quad (3)$$

Where, $\hat{p}, \hat{U}$ are the oscillating pressure and volume velocity amplitudes in form of complex number. H is the total energy power in wave direction and Q is the transversal heat exchange. The meaning of other parameters can be found in Ref. 6.

For the linear alternator, the following equations can be used to describe its operating:

$$\tau \frac{\hat{U}}{A} - (R_{elec} + jX_{elec}) \hat{I} = 0 \quad (4)$$

$$(R_{mech1} + jX_{mech1})\frac{\hat{U}}{A} + \frac{A}{j\omega C}\hat{U} + \tau\hat{I} = \hat{p}A \quad (5)$$

where

$$C = \frac{V_b}{\gamma p_m}, R_{elec} = r + R, X_{elec} = \omega L$$

$$X_{mech1} = \omega M - \frac{K}{\omega} - \frac{A^2}{\omega C}$$

Where, C is the acoustic compliance of the void volume of LA back space V_b measured about 1678cm^3 . γ is the specific heat ratio. R and X are real and imaginary part of a complex impedance. Subscript *elec* and *mech* mean electric and mechanical respectively.

For a given input pressure amplitude $\hat{p}$, the $\hat{I}$, $\hat{U}$ can be solved by (4)-(5). Then transformed acoustic power and output electric power can be given as follows:

$$W_a = \frac{1}{2} \text{Re}[\hat{p} \cdot \hat{U}^*] \quad (6)$$

$$W_e = \frac{1}{2} |\hat{I}|^2 \cdot R \quad (7)$$

Where, superscript * represents complex conjugate.

Coupling the numerical models of TASHE with LA, we can perform the simulation of the TASEG system. First of all, influences of the LA on the TASHE performance was investigated including volume velocity, pressure amplitude and acoustic power distributions, which are shown in Fig.2 and Fig.3 with helium at 2000W heating power, 2.0MPa mean pressure and 100Ω electric load resistance. The position axes begins from the loop outlet, then goes clockwise through the loop and resonance tube successively. From the distributions of pressure amplitude, volume velocity and acoustic power given in Figs.2 and 3, it can be found that the impact of the LA on the TASHE is relatively small. Moreover, the calculated frequency is reduced to 67.86Hz with LA compared with 68.22 Hz without LA. The calculated electric power is 35.5W and the transformed acoustic power is 44.0W.

From Figs. 2 and 3, the acoustic characteristics of the TASEG system are predominantly determined by the TASHE, so we can individually investigate the performance of the LA especially with different working frequencies and the electric load resistances. Experimentally, the working frequency of the system can

be increased or decreased by shortening or lengthening the resonance tube. Significant influence of the frequency on the LA performance is shown in Fig.4. It demonstrates that the output electric power reaches the maximum value at the resonant frequency of the LA which can be obtained from the mechanical and gaseous spring stiffness and the moving mass, while the acoustic-to-electric conversion efficiency (defined as W_e/W_a) is almost independent of the frequency.

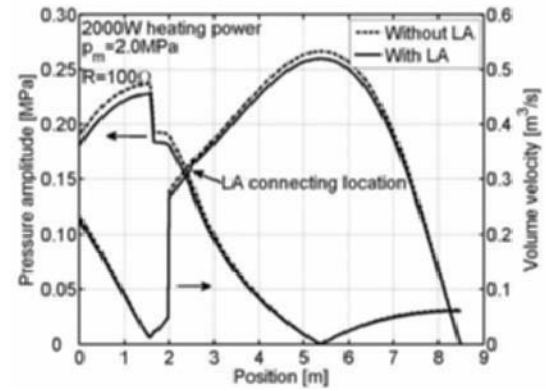


Fig. 2: Distributions of pressure amplitude and volume velocity of the TASEG.

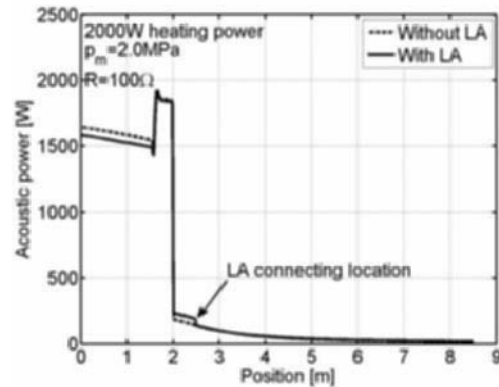


Fig. 3: Acoustic work distribution of the TASEG.

Besides the working frequency, the electric load resistance is another important factor determining the performance of the LA, whose influence is shown in Fig.5. The optimal electric power can be obtained at lower load resistance at given working frequency. Simultaneously, the acoustic-to-electric efficiency is low but increases with the increment of load resistance.

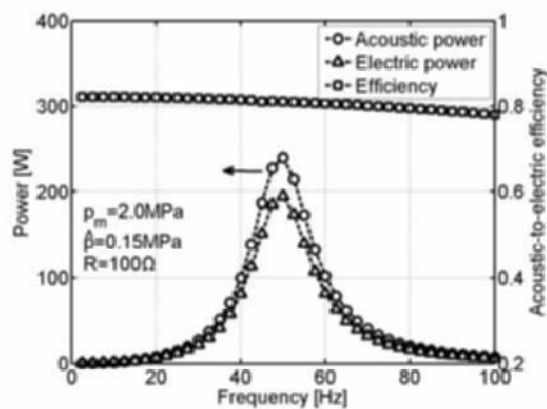


Fig. 4: Influence of the working frequency on the LA.

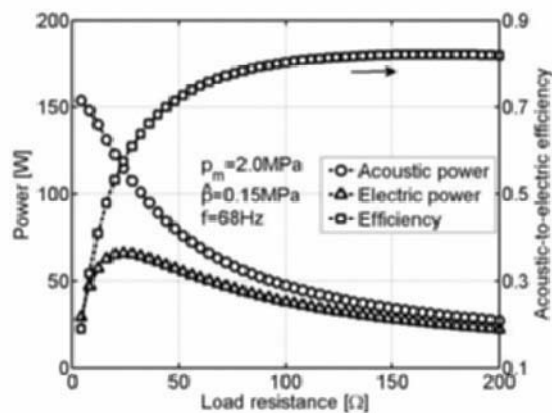


Fig. 5: Influence of the load resistance on the LA.

4. EXPERIMENTAL RESULTS

Preliminary experiments have been done to investigate the performance of both the TASHE and the LA. Taking the limitations of the winding current and pistons displacement and heating temperature (less than 650 °C) into consideration, some experimental results are given in Fig.6 and Fig.7. In Fig.6, the output electric power increases as the heating power increases and the load resistance decreases. A maximum electric power of 59 W is obtained under 2500 W heating power and 57 Ω load resistance. The computational electric powers are obtained using the measured pressure amplitude at the inlet of the LA. The discrepancies between the experimental and computational data are reasonably acceptable. So, the acoustic-to-electric transduction efficiency can be reasonably estimated in Fig.6. With a lower output electric power, the LA can give a maximum efficiency of about 0.88. In addition, the

analyzed working frequency gives little variation as the heating power changes. According to Fig.7, as the load resistance decreases under fixed heating power, the heating temperature increases and input pressure amplitude of the LA decreases, respectively.

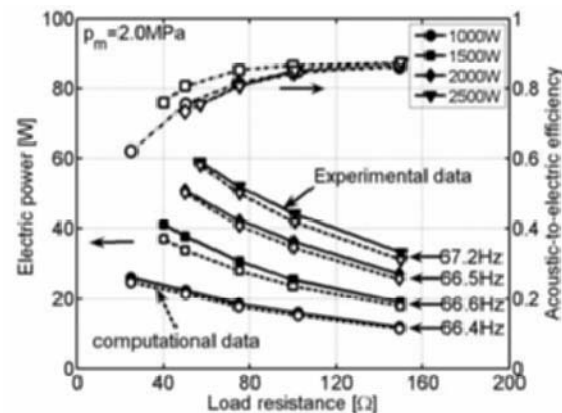


Fig. 6: Electric power and acoustic-to-electric efficiency vs. load resistance under different heating powers.

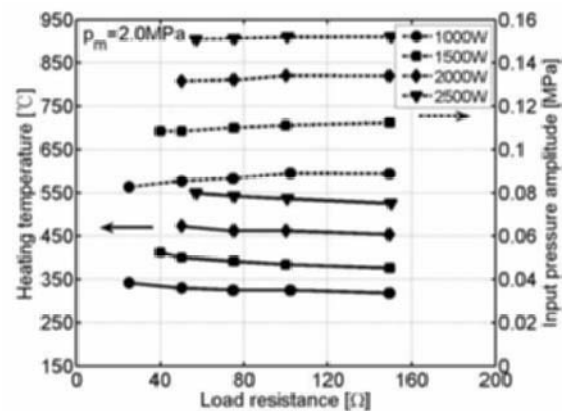


Fig. 7: Heating temperature and input pressure amplitude of the LA vs. load resistance under different heating powers.

To increase the output of electrical power, two modifications were made. First, a higher mean pressure of 2.5 MPa was tested. Secondly, a longer connecting pipe (about 1.1 m long, 50 mm in inner diameter) between the TASHE T-joint and the linear electrical alternator was used, which help to decrease acoustical power dissipation in the resonator. After these modifications, the whole system resonated at a frequency of 64 Hz. When the heating power was increased to about 2800 W and the load resistance was set at 100 Ω, the net output of electrical power achieved

100.5W.

Foundations of China (Grant No.50536040 and Grant No.50625620).

5. CONCLUSIONS

In this paper, a thermoacoustic-Stirling electric generator was constructed and studied, which consists of a thermoacoustic-Stirling heat engine with a tapered resonance tube and a dual-opposed linear alternator. According to the computational simulation, the impact of our LA on the performance of such a TASHE is very small. Moreover, the influences of frequency and electric load resistance are computationally investigated. It can be found that the output electric power is significantly increased near the resonant state of the LA. And a lower load resistance probably gives an optimal electric power but a lower efficiency, which is partly convinced later by experimental results, though experiments of lower load resistance is not performed because of the limitations of the winding current and piston displacement. After that, preliminary experiments have been done under different heating power. In the experiments, it also can be found that as the load resistance decreases, the heating temperature increases and the input pressure amplitude of the LA decreases slightly. Moreover, a maximum electric power of more than 100W and an estimated maximum LA efficiency of about 0.88 were achieved in the experiments. More detailed investigations on this topic will be needed in future.

6. ACKNOWLEDGMENTS

This work is financially supported by the Natural Sciences

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